Temperature Inversions in Relation to Frosts

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Professor E. J. Wickson
with pleasant memories of the days when we labored together on the frost problem in that wonderful western land and that glorious western climate of California.
A. M.

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BY

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Only in recent years have aerologists given much attention to the slow moving currents of the lower strata of the atmosphere. These differ greatly from the whirls and cataracts of both high and low levels which we familiarly know as the winds. The larger and more energetic air streams play a part in the formation of frost and their importance is not to be underestimated; but primarily it is a slow surface flow, almost a creeping, of the air near the ground which controls the temperature and is all important in frost formation. It is, therefore, of some importance to study the conditions which bring about this slow movement or displacement of air. It is true that there are times when with thorough mixing and ventilation, and little opportunity for slow displacement, temperature will fall to low points and damage from frost result; but such conditions are more properly described as cold waves, though the term is somewhat misleading, or as freezes. In such cases there is an unusual loss of heat by direct convection and the translation of masses of cold air. Strictly speaking, frosts are connected with temperature inversions brought about by vertical movement of the air, rather than horizontal; and are, therefore, essentially problems in *local air drainage.* The expression local air drainage requires some explanation. It was first used, so far as known, in explaining frost, by the writer, in his publication Frost Fighting, Bulletin 29, U. S. Weather Bureau, 1900. It was there shown that in the valleys of California a slow but well defined flow of the surface air can be traced and utilized in forecasting frosts. The condensed water vapor or fog can be seen drifting into the valleys or settling in the low places. There are well marked stream lines and one is led to believe that a mixture of air and water vapor of a given temperature, say 278° A is cooled by contact with the hill-tops; and under the influence of gravity and other causes flows down the slopes. The term air drainage has

[1] Some of the instruments used in this investigation were obtained through a grant from the Elizabeth Thompson Science Fund.

been objected to; and a recent writer[1] has insisted that the flow of air down a hillside is not comparable to a flow of water because water is an incompressible fluid where flow would be determined by gravity alone, while air is a compressible gas; and further because water may flow away leaving the space it occupied vacant. This writer forgets that as von Bezold and others have shown water or even a solid like iron will rise or fall without additional cooling or warming "*when it forms part of an endless chain* that glides frictionless over a roller and to which there has once been given a velocity, no matter how small."

It is well-known that soon after sunset, valleys and low places serve as catchment basins for slow moving air that is denser and colder. The hill-tops, terraces and even mountain tops if not too high, are in contact with air of higher temperature, which must be either an in-draft from warm surrounding strata, or the displaced air from below. How the circulation begins and how it is maintained are not clearly understood; and unfortunately we have no instruments sufficiently sensitive for our needs. The cooling of the lower levels, the warming of the upper levels and the existence of an inversion, are evidently not the result of a single cause. But one fact stands out strongly in all of the investigations thus far made; and that is, that where the *air is in motion*, there is less likelihood of frost than where the air is stagnant. This may be called the first law of frost formation.

One factor in establishing the circulation is that slopes, especially those facing west or southwest, have been heated by insolation during the day and therefore radiate more rapidly, since radiation is a function of the absolute temperature; but the energy thus radiated is not absorbed by any layer of vapor and dust particles, as generally is the case with the radiation from the lower levels. The valleys and low levels lose heat by radiation; but soon after sunset there is formed a thin blanket of condensed vapor, which interferes with free radiation and checks the rate of cooling. The air at the higher level is robbed of its vapor and dust nuclei, becoming more and more like a pure gas and permitting freer radiation. Mixed air and vapor is lighter than dry air per unit volume; and thus moist air would naturally tend to rise. The condensed vapor, however, must be regarded in a different light from the vapor before condensation. In condensing and also, but to less degree in congealing into frost flakes, heat is set free in the sense that molecular energy is decreased. This heat is not shown as a direct rise in

[1] Monthly Weather Review, October, 1914, p. 583.

temperature but does serve to prevent fall in temperature, such as expansion due to rising would produce. Thus we have near the ground an increasing load of condensed vapor or vapor near the condensing point, which either crystallizes as frost with further cooling or is carried away by convective currents.

We see then that there are various conflicting processes; for there is gain and loss of heat by radiation (the upper slopes losing heat by radiation and the lower air masses gaining heat); retardation or acceleration of rate of temperature change by the change in state of the water vapor; direct gain or loss of heat by convection or the actual translation of cold and warm air masses; and finally some slight gain or loss by conductivity.

Unfortunately the term frost has been used as synonymous with lowest temperature, whereas it more properly is simply an indication of the existence of sufficient water vapor changed into ice in the form of spicular crystals. Such deposit does not necessarily indicate the place of lowest temperature, for with other than saturation conditions, lower temperatures may prevail without the crystals forming.

Some good illustrations of inversions of temperature are shown in the accompanying diagrams (Figures 1, 2, and 3).

Figure 1 illustrates a remarkable inversion which occurred January 5, 1904, when the temperature at the valley station fell to 233°A. There was also an inversion of similar character on the succeeding night. In Figure 2 is shown an inversion occurring on February 25, 1914, which is of special interest as the effective cause of cooling did not begin soon after sunset, as is the case with most inversions; and in fact did not manifest itself until *long after midnight*. Figure 3 illustrates typical early fall and late spring inversions, of special interest to gardeners and truck farmers.

In all of these it will be noticed that there is a rapid rise in temperature at the lowest level, shortly after sunrise and a slow rise at the base, and still slower at the summit. The respective heights of the three stations are valley, 18 metres, base of hill 66 metres, and summit 200 metres above sea level. This rapid rise at the valley level is significant for it indicates that with the formation of convective currents due to insolation, there is air movement and effective heating. One might infer from this that the effective cause of cooling is not radiation but the rapid dying out of convectional currents near the ground after sunset, despite any acceleration due to displacement by the slow, down-moving air from the slopes. The mass of air surrounding the summit and hilltops is in the main warmer, as we have seen; and remains relatively warm throughout the night, since radiation from air is less rapid than from the hillsides. Apparently then there is a slow flow of air down the sides into the valley; but no marked convectional interchange between the different levels. It should be noted that in the valley under discussion (the Neponset) the western slopes are far distant, so that in this case, the contour is not such as to confine the descending currents. It seems also plain from these inversions that the principle reason why the summit temperature remains high during the night is because of the existence of a moderate air movement and consequent mixing. Frequent eye observation of the rate of ascent of smoke from the valley on quiet, clear afternoons have enabled members of the Observatory staff to surmise the existence of inversion and to anticipate the frosts of the next morning, with a high accuracy. Any change in velocity or direction of air flow is accompanied with fluctuation in temperature. Discussion of the pressure distribution and general circulation must be restricted, for lack of space, and at present it will be enough to say that there are certain types of storm movement easily recognizable, which are followed by frosts. Gusty northwest winds, dying out at sunset, with unclouded skies and low and decreasing humidity above 100 metres but increasing in the lower levels, are significant local conditions preceding inversion and favoring frost.

Some writers have made use in their frost discussions of the adiabatic rate of fall of temperature, which is 0.98 degree for each hundred metre rise; but no such condition is found to occur at times of frost. On the contrary, as we have seen above, there is gain and loss of heat in various ways, and adiabatic equilibrium is out of the question. Neither the adiabatic rate for dry air nor for saturated air holds from the ground up to 200 metres. Instead of a fall there is a rise in temperature.

Nearly always as the temperature rises the humidity falls. Unfortunately our instruments for recording humidity are unsatisfactory. Relative humidity, standing by itself and as ordinarily expressed is very misleading; and in fact means a ratio in which one term is suppressed. No proper study of frost or temperature inversion can be made without a full and definite knowledge of the behavior of the water vapor and dust content. A form of instrument devised by the writer is a decided improvement over the usual form of hygrograph. It is known as a Saturation Deficit Recorder and gives a continuous record of the weight of the vapor in grams per unit volume. The temperatures are given in degrees absolute but the record sheet also is graduated to show the saturation weights for each degree. The thermograph portion of the instrument (see Figure 4) therefore records the appropriate weight of the water vapor per cubic metre at saturation and the hygrograph portion gives the percentage existing. The difference between the two is the saturation deficit, a quantity that may be used to advantage in discussions of frost formation or in the more general problem of the changes in a given volume of moist air as it rises or falls or is transported from a region of high to a region of low pressure.

It is to be regretted that we have no method of recording continuously what von Bezold has termed the *mixing ratio* or the mass of vapor mixed with a unit mass of dry air expressed as a fraction of this latter unit, nor that other term, which he calls the *specific humidity* or the quantity of vapor in a unit mass of moist air expressed in fractional parts of this unit. There is a difference too between vapor pressure and absolute humidity although the two are often considered as equivalent. The record of the mixing ratio would be important in frost work since for any given change of level, the change in the mixing ratio would give the quantity of ice deposited, not in this case, due to ascent of the air but by contact with the hillsides cooled by rapid radiation, or with the floor of the valley which also acts as a condensing surface. Moreover the quantity of water (or frost crystals) thus separated from the air would give an indication of the intensity of the up-and-down movement of the air and vapor. We have, indeed, in frost conditions a problem somewhat similar to that in certain cloud formations, billow and bar, less pronounced but none the less phenomena of moving air strata of different temperatures and densities in close proximity. It may be pointed out too as Neuhoff has shown in his reconstruction of the Hertz diagram, that at 273°A, altitude lines run parallel to pressure lines at equal distances from each other for equal pressure changes and hence the isothermal change of altitude at freezing temperature is proportional to the quantity of water present. Practically one gram of freezing water is equivalent to a change of level of 27 metres.

A more direct form of instrument is that of the Foxboro type, the record of which is shown in Figure 5 where there is continuously recorded not only the temperature but also the temperature of evaporation. The pressure of the aqueous vapor can be readily determined from the formula as given by Ferrel (Report C. S. O. 1886 App. 24) or directly from Table 150, Smithsonian Physical Tables 1914, p. 157. The dew-point, relative humidity, and humidity term 0.378 e which occurs in the formula for density of air containing aqueous vapor at pressure e can be easily obtained. This instrument gives more accurate readings if the two thermometers are placed near a small fan or other ventilating device. It is also preferable that this instrument be not inclosed in the usual louvred shelter, nor at the customary elevation of two metres above the ground; but as near the ground as possible.

Records of relative humidity as usually given are of doubtful value. As stated above this term standing by itself means nothing.

It is also necessary to pay special attention to the purity of the water and the cleanness of the muslin used on the wet-bulb for evaporating the film of water. The pressure of saturated aqueous vapor varies somewhat at temperatures near 273°A, depending upon whether the radiation is from a water or an ice surface. The following short table illustrates this difference.

	Temperature	Vapor pressure		Temperature	Vapor pressure
Over water,	270° A	4.9 Kbs	Over ice,	270° A	4.7 Kb
	271	5.3 "		271	5.2 "
	272	5.7 "		272	5.6 "
	273	6.1 "		273	6.1 "

It is important to obtain reliable records of the amount of water vapor present; and if possible the changes which this quantity undergoes. We believe that one source of cooling is the abstraction of considerable moisture from the air; and consequent increase in radiation. A copious deposit of frost, however, does not necessarily indicate the region of lowest temperature.

We have seen that the motion of the air is complicated at times of frost, and so too the motions and changes of form of the vapor. In a sense they are independent variables. A cubic metre of pure, dry air at 283° weighs 1247 grams; but if cooled to 273° weighs 46 grams more. A cubic metre of mixed air and saturated vapor at 283° weighs 1242 grams or 5 grams less; and if this were cooled ten degrees the mixture would weigh three grams less than the same volume of pure dry air. In each case the mixture of air and water vapor weighs less than the air by itself. One would think that adding water vapor which while light still has weight, would make the total weight the sum of both. It really is so, notwithstanding the above figures; and the explanation of the puzzle is found in an increase in pressure and consequent expansion, so that the volume of the air and saturated vapor is greater than one cubic metre. Since then a cubic metre of air and saturated vapor weighs less than a cubic metre of dry air at freezing temperature, we may expect moist air to rise and dry air to fall. Consequently if in addition to falling temperature there is also a drying of the upper air, we shall have an accelerated settling or descent of cold dry air to the ground which of course favors the formation of frost. The water vapor plays also another role besides that of varying the weight per unit volume. The heat received by the ground consists of waves of a certain wave-length; but the heat re-radiated by the ground consists of waves of longer wave-length, and these so-called long waves (12 thousandths of a millimetre) are readily absorbed by water vapor. Thus water vapor acts like a blanket and holds the heat, preventing loss of heat by radiation to space. Further on we shall speak of the high specific heat of both water vapor and ice as compared with air and show the bearing of this in frost fighting; but at present we may from what precedes formulate the second law of frost formation as follows:

" Frost is more likely to occur when the upper air is dry than when it is moist." It is also true that a dusty atmosphere is less favorable for frost than a dust free atmosphere. Thus we may generalize and say that whatever favors clear, still, dry air favors frost. The theory of successful frost fighting then is to interfere with or prevent these processes which as we have seen facilitate cooling close to the ground. In what way can this best be done ?

PROTECTION FROM INJURY BY FROST.

The most natural way would be to conserve the earth's heat, which could be accomplished by covering plants with cloth, straw, newspaper, or perhaps better still, modern weather proof sheeting or in still another way by a cover of dense smoke, generally called a smudge. A second method would be by means of direct application of heat; and this is accomplished in orange groves by means of improved orchard heaters. Large fires waste heat and are neither economical nor effective. A third method would be based upon some method of mixing the air strata and getting the benefit of the warmer higher levels. Fourth, advantage might be taken of some agency such as water or water vapor, having a high specific heat. Finally, if the crop is of a certain character such as the cranberry, it will be found advisable to use sand, and to drain and clean, here again making use of the specific heat of some intermediary. And furthermore any one of these methods may be combined with some other method.

Regarding the first method, that of covers, it may be said that the practice goes back to the early husbandmen; but only in the last few years has the true function of the cover been properly interpreted and we are still far from obtaining maximum efficiency, nor is there yet a suitable, scientific cover available. Any medium that interferes with loss of heat through free radiation before and after sunset is a cover. The best type of cover is a cloud; and clouds whether high or low are good frost protectors. On cloudy nights there is little likelihood of frost; nor do inversions occur. We have mentioned above the fact that the earth radiates the heat it has received not in the same but in longer wave-lengths. These are easily trapped and held by the vapor of water. Furthermore the rate of radiation is a function of the absolute temperature and so the rapidity of loss depends somewhat upon the heat received. Therefore the cover should be used as early in the day as possible that is just before sunset. Aside from the water cover or vapor cover there are cheap cloth screens, fibre screens and also lath screens.

The second method, that of direct heating has met with much success in the orange groves of California and elsewhere. Modern heating methods date from experiments begun in 1895. A number of basic patents granted to the writer in this connection have been dedicated to the public. At the present time there are on the market some twenty forms of heaters, which have been described with more or less detail in farm journals and official publications. It is not necessary to refer to them further here. The fuel originally used was wood, straw and coal but these are now supplanted by crude oil or distillate. It has also been seriously proposed to use electric heaters, also to use gas. Properly installed and handled there is no difficulty in raising the temperature of even comparatively large tracts five degrees and maintaining a temperature above freezing, thus preventing refrigeration of plant tissue.

The third method, that of utilizing the heat of higher levels by mixing has not yet been commercially developed; while the methods of applying water, either in the spraying of trees or the running of ditches or the flooding of bogs, together with methods of sanding, cleaning and draining have all been proven helpful. Methods available and most effective in one section may not necessarily be effective in another section or with different crop requirements. Certain devices most effective in the groves of California may not answer in Florida or Louisiana because of entirely different weather conditions. Along the Gulf coast where water is available it may be advantageously used to hold back ripening and retard development until after the cold waves of middle and late February have passed, whereas on the west coast, conditions are very different, water having a definite value and the critical periods coming in late December or early January.

In what precedes stress has been laid chiefly upon the fall of temperature and the congelation of the water vapor. There is, however, another important matter connected with injury to plant tissue and that is the rise in temperature after the frost. A too rapid defrosting may do considerable damage where no damage was originally done by the low temperature. It is in this connection that water may be used to great advantage. Water, water-vapor and ice, compared with other substances have remarkably high specific heats. If the specific heat under constant pressure of water be taken as unity, that of ice is 0.49; of water vapor 0.45 and of air 0.24. Or in a general way we may say that water has four times the capacity for heat that air has. Therefore, it is apparent that water will serve excellently to prevent rapid change in temperature. This is important at sunrise and shortly after when some portion of the chilled plant tissue may be exposed to a warming sufficient to raise the temperature of the exposed portion ten degrees in an hour.

The latent heat of fusion of ice is 79.6 calories and the latent heat of vaporization of water is nearly 600 small calories or therms per gram. Therefore in the process of changing from solid to liquid to vapor as from ice to water to vapor a large amount of heat is liberated. This does not mean as is generally assumed that the air will be warmed but it does mean a retardation of temperature change. And it is essential that the restoration of the tissues and juices to their normal state be accomplished gradually, neither too rapidly nor yet too slowly. There is probably an optimum temperature for thawing or defrosting frozen fruits and flowers.

Finally the temperature records as ordinarily obtained need careful interpretation. It may be that the freezing point of liquids under pressure in the plant cells or exposed to the air through the stomata is not the same as in the free air. It is unfortunate too that in most places data showing temperatures of soil, plant and air are of doubtful character. A word of warning may be given against the too ready acceptance of Weather Bureau records made in cities and on the roofs of buildings. Garden and field conditions vary greatly from these. It is further advisable to obtain a continuous record of the temperature of evaporation such as is shown by the records herewith. The two temperature curves made simultaneously and easily read at any moment enable the gardener or orchardist to forecast the probable minimum temperature of the ensuing ten or twelve hours. But not always, and some study is necessary. A slight increase in cloudiness or a slight shift in wind direction will prevent the fall in temperature which otherwise seemed probable. With a persistent inversion of temperature there is sometimes an increasing absolute humidity. In fact the problem is many sided and we must consider the motion of the air vertically as well as horizontally. Air gains and loses heat chiefly by convection, and any gain or loss by conduction may be neglected. The plant gains heat by convection, radiation and perhaps by conduction of an internal rather than surface character. The ground gains and loses heat chiefly by radiation. But the whole process is complicated, nor are the rates of change uniform. Frosts generally are preceded by a loss of heat from the lower air strata, due to convection and a horizontal translation of the air. Then follows an equally rapid and great loss of heat by free radiation. There are minor changes such as the setting free of heat in condensation and its utilization in evaporation but these latent heats are of less importance than the actual transference of the air and vapor and the removal of the latter as an absorber and retainer of heat.

Frosts are recurrent phenomena reasonably certain to occur within given dates; and as pointed out above, the cumulative losses are considerable. Methods of protection to be serviceable must be available for more than one occasion, for there is no profit in saving a crop on one night and losing it on the succeeding night. But the effort is worth while. Consider that the horticulturist regularly risks the labor of many months on the temperatures of a few hours. An efficient frost fighting device is in a way the entering wedge for solving problems of climate control. One may not take a crop indoors, it is true, but there is no valid reason, in the light of what has been already accomplished, why at critical periods which may be anticipated, the needed volume of surface air may not be sufficiently warmed; and the losses which have heretofore been considered inevitable, be prevented.

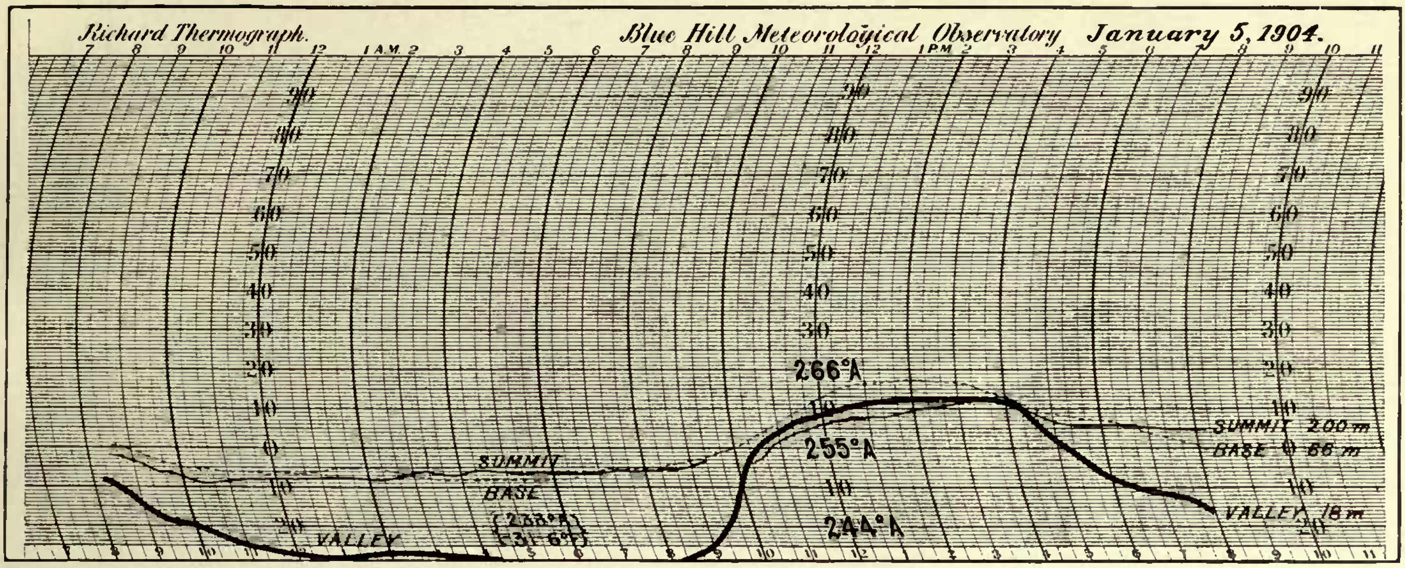

FIG. 1. WINTER TYPE. MARKED COOLING 8 P.M. TO 12 MIDNIGHT, MARKED WARMING 8 A.M. TO 11 A.M.

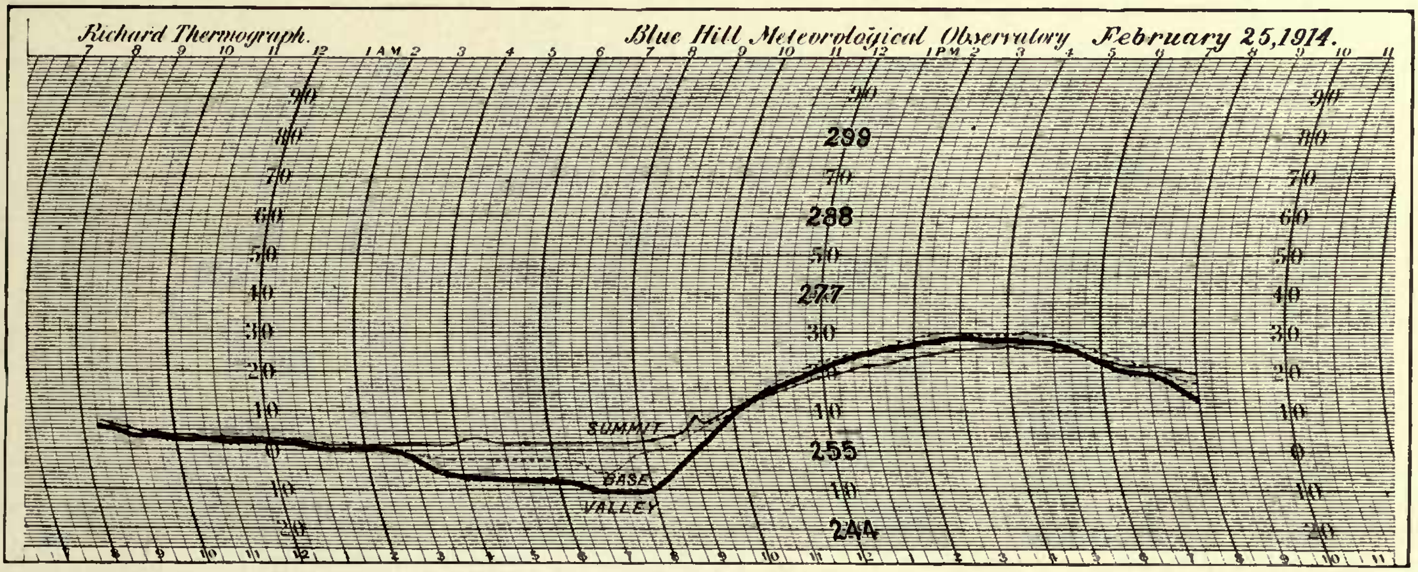

FIG. 2. UNUSUAL TYPE. MARKED COOLING BEGAN 2.20 A.M.

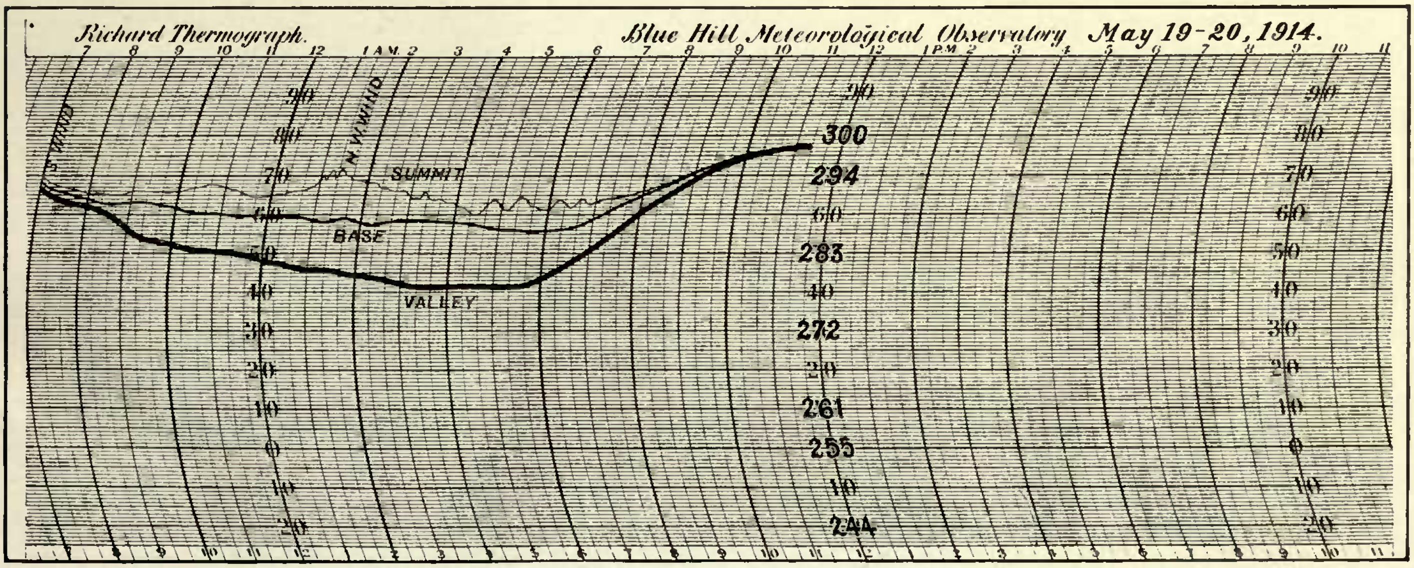

FIG. 3. TYPICAL LATE SPRING FROST.

TEMPERATURE INVERSIONS.

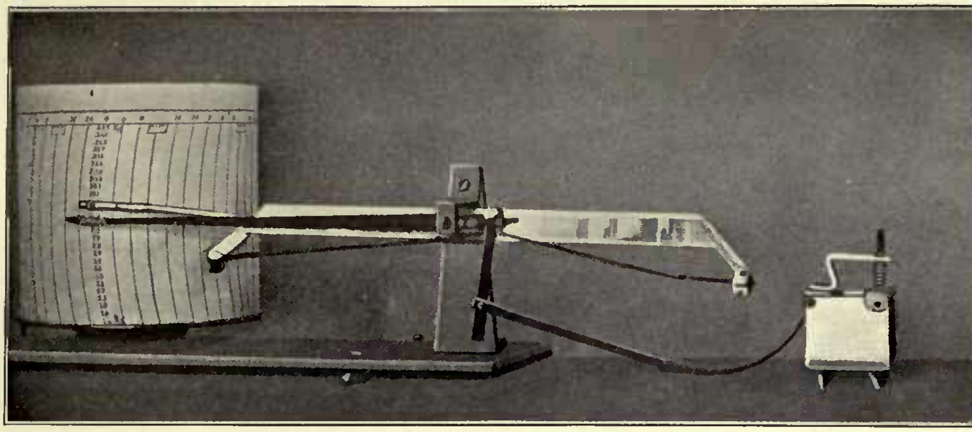

Fig. 4. Saturation Deficit Recorder.

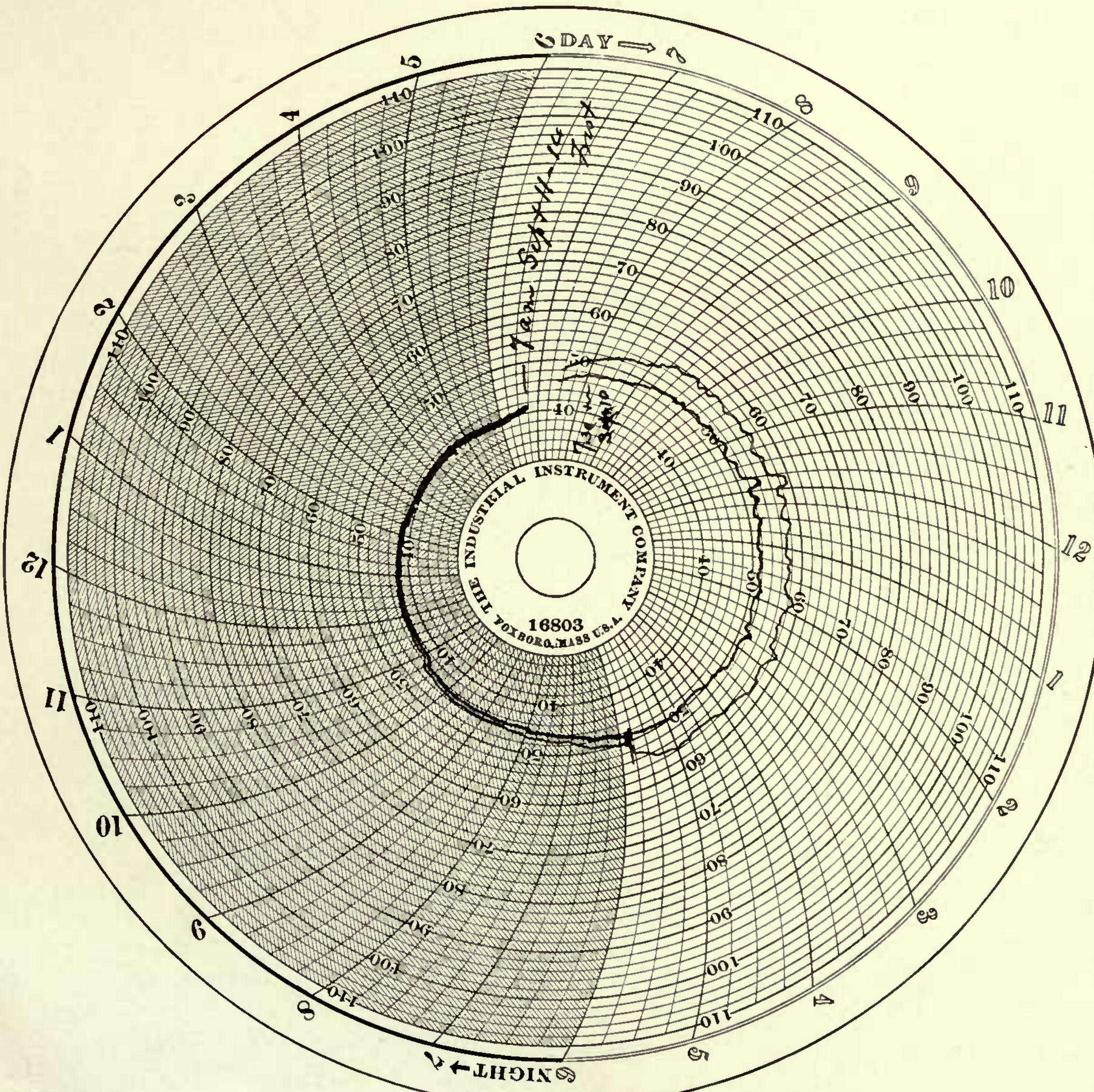

Fig. 5. Serviceable Dry and Wet Thermograph.

METEOROLOGICAL INSTRUMENTS.

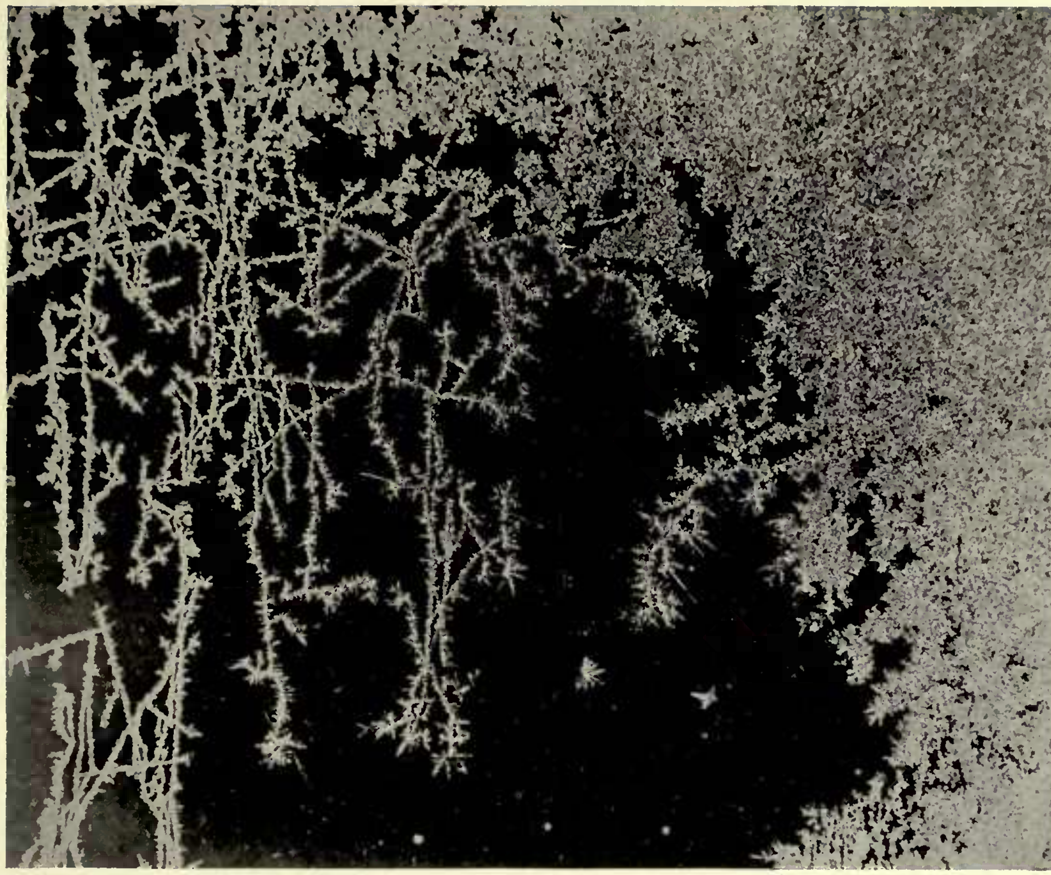

Fig. 6. Frost Crystals. Actual Size.

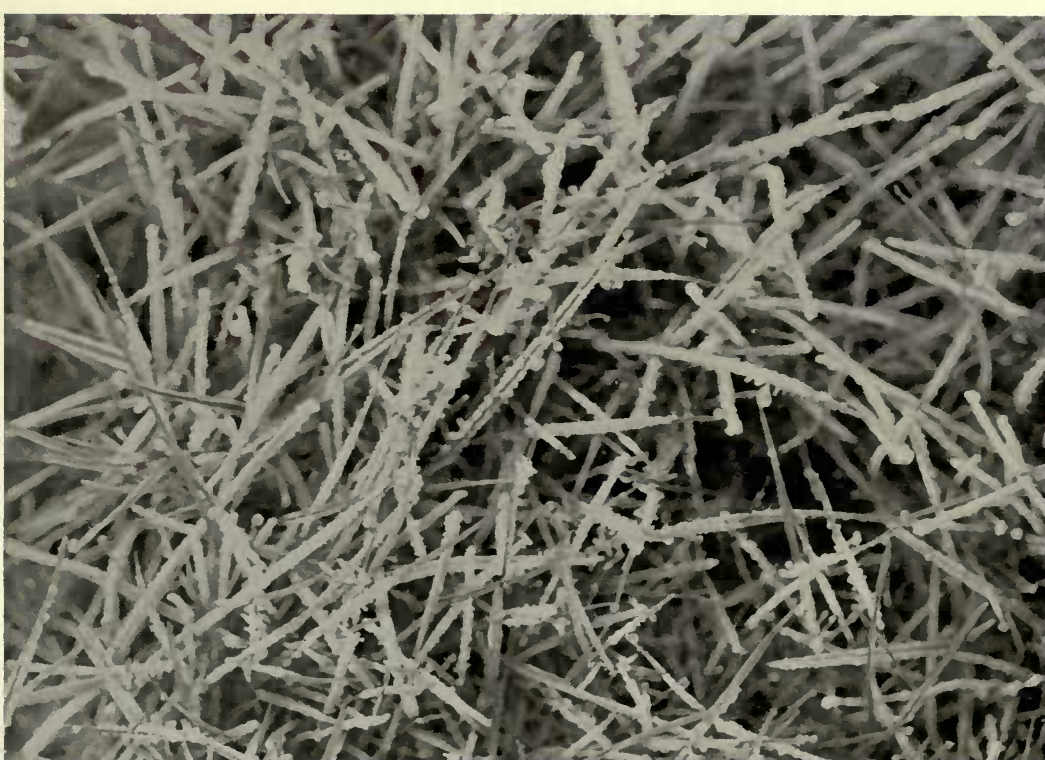

Fig. 7. Frost Crystals on Grass.

FROST CRYSTALS.

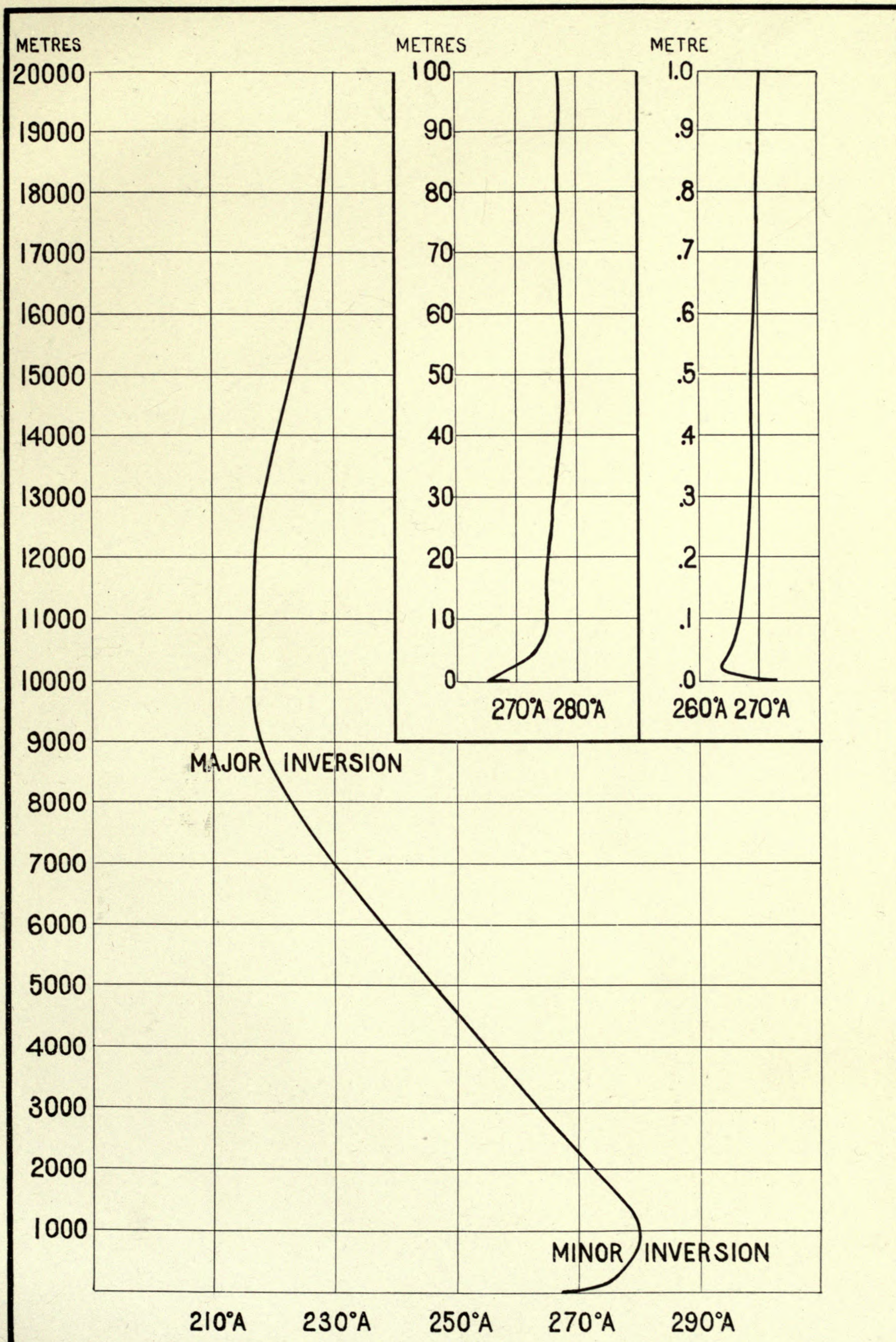

FIG. 8.

TEMPERATURE INVERSIONS AT TIMES OF FROST.